# Unit OS5: Memory Management

5.4. Physical Memory Management



## Roadmap for Section 5.4.

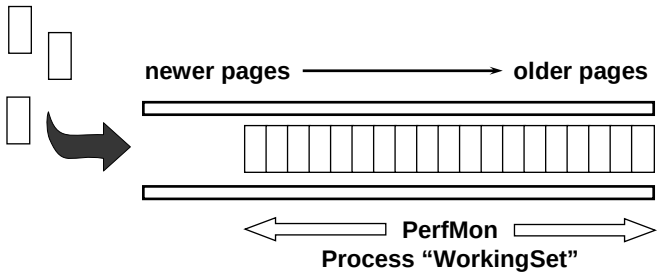
- From working sets to paging dynamics
- Birth of a process working set
- Working set trimming, heuristics
- Paging, paging dynamics
- Hard vs. soft page faults
- Page files

# Working Set

- Working set: All the physical pages "owned" by a process
  - Essentially, all the pages the process can reference without incurring a page fault
- Working set limit: The maximum pages the process *can* own
  - When limit is reached, a page must be released for every page that's brought in ("working set replacement")
  - Default upper limit on size for each process
  - System-wide maximum calculated & stored in MmMaximumWorkingSetSize
    - approximately RAM minus 512 pages (2 MB on x86) minus min size of system working set (1.5 MB on x86)
    - Interesting to view (gives you an idea how much memory you've "lost" to the OS)
  - True upper limit: 2 GB minus 64 MB for 32-bit Windows

4

# Working Set List




- A process always starts with an empty working set
  - It then incurs *page faults* when referencing a page that isn't in its working set
  - Many page faults may be resolved from memory (to be described later)

5

## Birth of a Working Set

- Pages are brought into memory as a result of page faults
  - Prior to XP, no pre-fetching at image startup
  - But readahead is performed after a fault
    - See MmCodeClusterSize, MmDataClusterSize, MmReadClusterSize
- If the page is not in memory, the appropriate block in the associated file is read in
  - Physical page is allocated
  - Block is read into the physical page
  - Page table entry is filled in
  - Exception is dismissed
  - Processor re-executes the instruction that caused the page fault (and this time, it succeeds)
- The page has now been “faulted into” the process “working set”

6

## Prefetch Mechanism

- First 10 seconds of file activity is traced and used to prefetch data the next time
  - Also done at boot time (described in Startup/Shutdown section)
- Prefetch “trace file” stored in \Windows\Prefetch
  - Name of .EXE-<hash of full path>.pf
- When application run again, system automatically
  - Reads in directories referenced
  - Reads in code and file data
    - Reads are asynchronous
    - But waits for all prefetch to complete

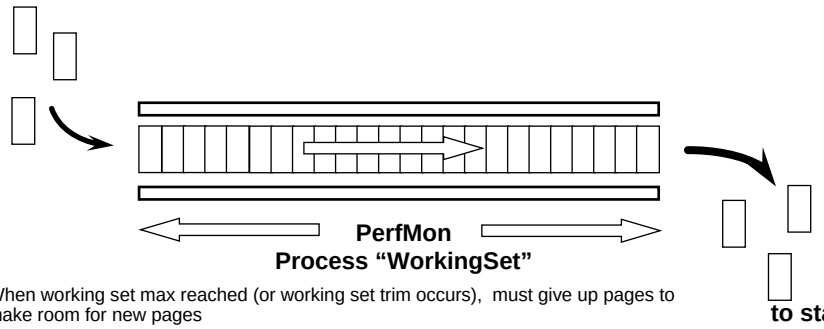
7

# Prefetch Mechanism

- In addition, every 3 days, system automatically defrags files involved in each application startup
- Bottom line: Reduces disk head seeks
  - This was seen to be the major factor in slow application/system startup

8

# Working Set Replacement




- When working set max reached (or working set trim occurs), must give up pages to make room for new pages
- Local page replacement policy (most Unix systems implement global replacement)
  - Means that a single process cannot take over all of physical memory unless other processes aren't using it
- Page replacement algorithm is least recently accessed (pages are aged)
  - On UP systems only in Windows 2000 – done on all systems in Windows XP/Server 2003
- New VirtualAlloc flag in XP/Server 2003: MEM_WRITE_WATCH

9

# Soft vs. Hard Page Faults

- Types of “soft” page faults:
  - Pages can be faulted back into a process from the standby and modified page lists
  - A shared page that’s valid for one process can be faulted into other processes
- Some hard page faults unavoidable
  - Process startup (loading of EXE and DLLs)
  - Normal file I/O done via paging
    - Cached files are faulted into system working set
- To determine paging vs. normal file I/Os:
  - Monitor Memory->Page Reads/sec
    - Not Memory->Page Faults/sec, as that includes soft page faults
  - Subtract System->File Read Operations/sec from Page Reads/sec
  - Or, use Filemon to determine what file(s) are having paging I/O (asterisk next to I/O function)
  - Should not stay high for sustained period

10

# Working Set System Services

- Min/Max set on a per-process basis
  - Can view with !process in Kernel Debugger
- System call below can adjust min/max, but has minimal effect prior to Server 2003
  - Limits are “soft” (many processes larger than max)
  - Memory Manager decides when to grow/shink working sets
- New system call in Server 2003 (SetProcessWorkingSetSizeEx) allows setting hard min/max
- Can also self-initiate working set trimming
  - Pass -1, -1 as min/max working set size (minimizing a window does this for you)

**Windows API:**
**SetProcessWorkingSetSize(**
**HANDLE hProcess,**
**DWORD dwMinimumWorkingSetSize,**
**DWORD dwMaximumWorkingSetSize)**

11

# Locking Pages

- Pages may be locked into the process working set
  - Pages are guaranteed in physical memory (“resident”) when any thread in process is executing

```
Windows API:
status = VirtualLock(baseAddress, size);
status = VirtualUnlock(baseAddress, size);
```

- Number of lockable pages is a fraction of the maximum working set size
  - Changed by SetProcessWorkingSetSize
- Pages can be locked into physical memory (by kernel mode code only)
  - Pages are then immune from “outswapping” as well as paging

```
MmProbeAndLockPages
```

12

# Balance Set Manager

- Nearest thing Windows has to a “swapper”
  - Balance set = sum of all inswapped working sets
- Balance Set Manager is a system thread
  - Wakes up every second. If paging activity high or memory needed:
    - trims working sets of processes
    - if thread in a long user-mode wait, marks kernel stack pages as pageable
    - if process has no nonpageable kernel stacks, “outswaps” process
    - triggers a separate thread to do the “outswap” by gradually reducing target process’s working set limit to zero
- Evidence: Look for threads in “Transition” state in PerfMon
  - Means that kernel stack has been paged out, and thread is waiting for memory to be allocated so it can be paged back in
- This thread also performs a scheduling-related function
  - CPU starvation avoidance - already covered

13

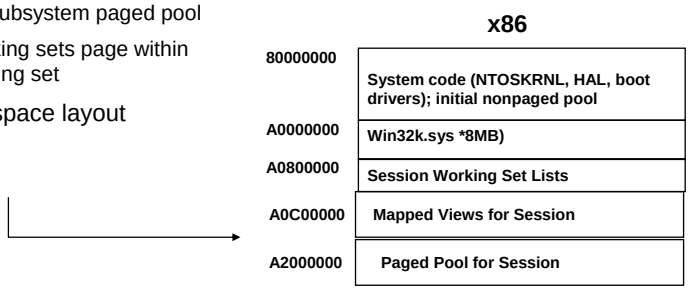
# System Working Set

- Just as processes have working sets, Windows' pageable system-space code and data lives in the "system working set"
- Made up of 4 components:
  - Paged pool
  - Pageable code and data in the exec
  - Pageable code and data in kernel-mode drivers, Win32K.Sys, graphics drivers, etc.
  - Global file system data cache
- To get physical (resident) size of these with PerfMon, look at:
  - Memory | Pool Paged Resident Bytes
  - Memory | System Code Resident Bytes
  - Memory | System Driver Resident Bytes
  - Memory | System Cache Resident Bytes
  - ⑤ Memory | Cache bytes counter is total of these four "resident" (physical) counters (not just the cache; in NT4, same as "File Cache" on Task Manager / Performance tab)

14

# Session Working Set

- New memory management object to support Terminal Services in Windows 2000/XP/Server 2003
- Session = an interactive user
- Session working set = the memory used by a session
  - Instance of WinLogon and Win32 subsystem process
  - WIN32K.SYS remapped for each unique session
    - Win32 subsystem objects
    - Win32 subsystem paged pool
  - Process working sets page within session working set
- Revised system space layout




15

# Managing Physical Memory

- System keeps unassigned physical pages on one of several lists
  - Free page list
  - Modified page list
  - Standby page list
  - Zero page list
  - Bad page list - pages that failed memory test at system startup
- Lists are implemented by entries in the “PFN database”
  - Maintained as FIFO lists or queues

16

# Paging Dynamics

- New pages are allocated to working sets from the top of the free or zero page list
- Pages released from the working set due to working set replacement go to the bottom of:
  - The modified page list (if they were modified while in the working set)
  - The standby page list (if not modified)
    - Decision made based on “D” (dirty = modified) bit in page table entry
  - Association between the process and the physical page is still maintained while the page is on either of these lists

17

# Standby and Modified Page Lists

- Modified pages go to modified (dirty) list
  - Avoids writing pages back to disk too soon
- Unmodified pages go to standby (clean) list
- They form a system-wide cache of “pages likely to be needed again”
  - Pages can be faulted back into a process from the standby and modified page list
  - These are counted as page faults, but not page reads

18

# Modified Page Writer

- When modified list reaches certain size, modified page writer system thread is awoken to write pages out
  - See MmModifiedPageMaximum
  - Also triggered when memory is overcomitted (too few free pages)
  - Does not flush entire modified page list
- Two system threads
  - One for mapped files, one for the paging file
- Pages move from the modified list to the standby list
  - E.g. they can still be soft faulted into a working set

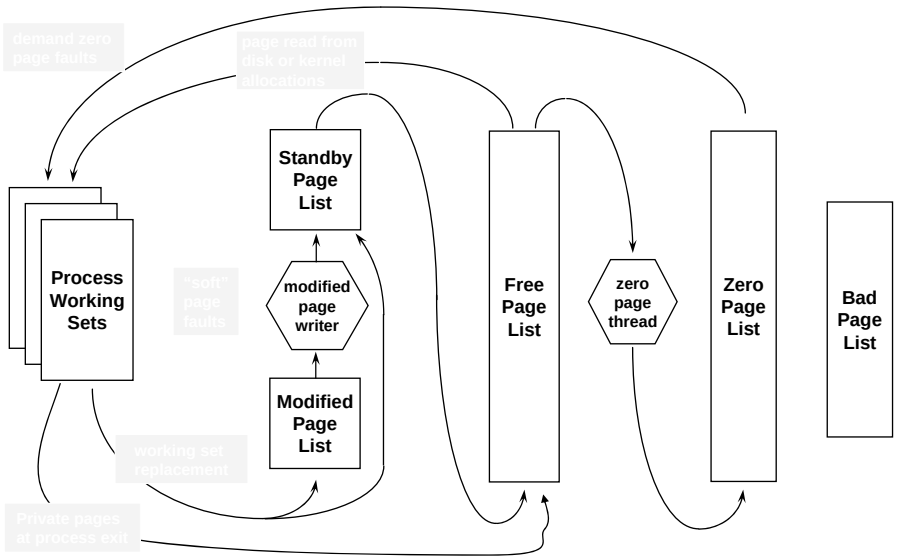
19

# Free and Zero Page Lists

- Free Page List
  - Used for page reads
  - Private modified pages go here on process exit
  - Pages contain junk in them (e.g. not zeroed)
  - On most busy systems, this is empty
- Zero Page List
  - Used to satisfy demand zero page faults
    - References to private pages that have not been created yet
  - When free page list has 8 or more pages, a priority zero thread is awoken to zero them
  - On most busy systems, this is empty too

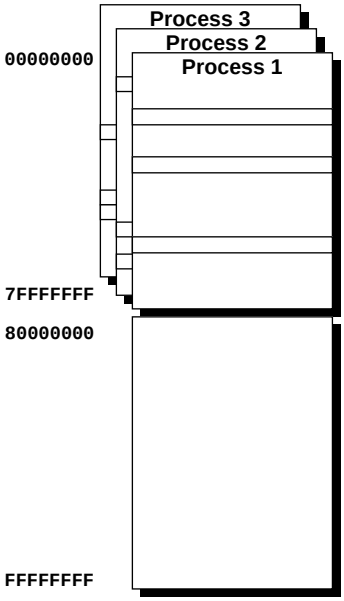
20

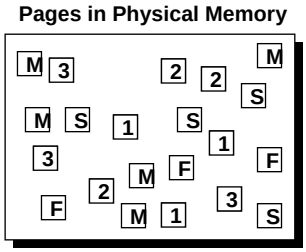
# Paging Dynamics




21

# Working Sets in Memory




- As processes incur page faults, pages are removed from the free, modified, or standby lists and made part of the process working set
- A shared page may be resident in several processes' working sets at one time (this case not illustrated here)

22

# Page Frame Number-Database

- One entry (24 bytes) for each physical page
  - Describes state of each page in physical memory
- Entries for active/valid and transition pages contain:
  - Original PTE value (to restore when paged out)
  - Original PTE virtual address and container PFN
  - Working set index hint (for the first process...)
- Entries for other pages are linked in:
  - Free, standby, modified, zeroed, bad lists (parity error will kill kernel)
- Share count (active/valid pages):
  - Number of PTEs which refer to that page; 1->0: candidate for free list
- Reference count:
  - Locking for I/O: INC when share count 1->0; DEC when unlocked
  - Share count = 0 & reference count = 1 is possible
  - Reference count 1->0: page is inserted in free, standby or modified lists

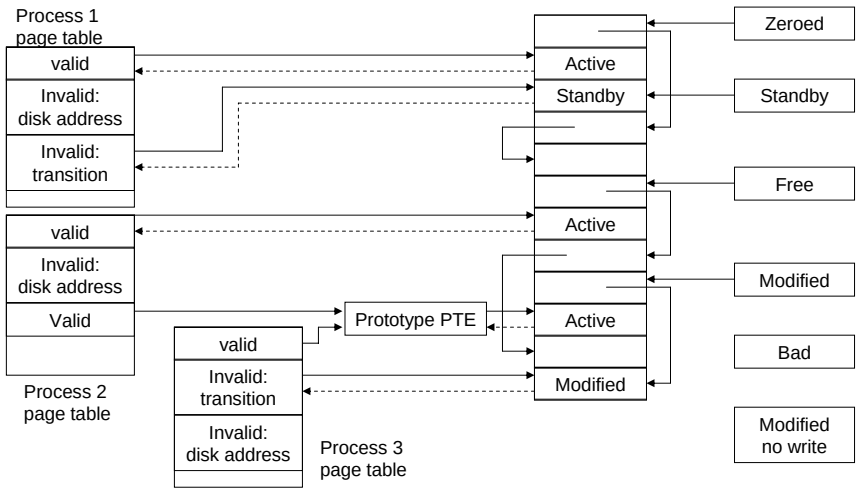
23

# Page Frame Database – states of pages in physical memory

| Status | Description |
|---|---|
| Active/valid | Page is part of working set (sys/proc), valid PTE points to it |
| Transition | Page not owned by a working set, not on any paging list<br>I/O is in progress on this page |
| Standby | Page belonged to a working set but was removed; not modified |
| Modified | Removed from working set, modified, not yet written to disk |
| Modified no write | Modified page, will not be touched by modified page write, used by NTFS for pages containing log entries (explicit flushing) |
| Free | Page is free but has dirty data in it – cannot be given to user process – C2 security requirement |
| Zeroed | Page is free and has been initialized by zero page thread |
| Bad | Page has generated parity or other hardware errors |

24

# Page tables and page frame database

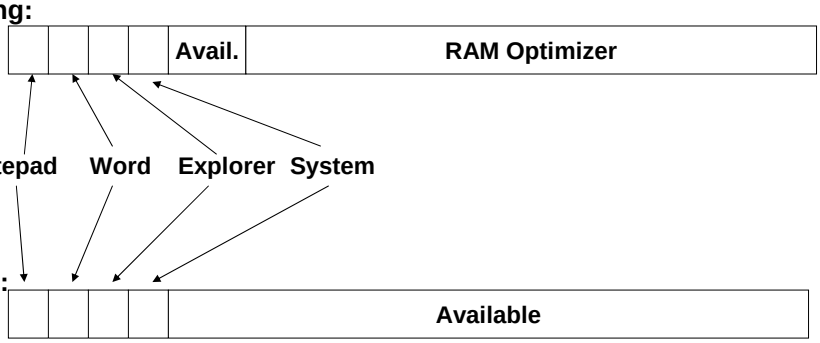



25

# Why “Memory Optimizers” are Fraudware

**Before:**


**During:**




**After:**




**See Mark’s article on this topic at**
**http://www.winnetmag.com/Windows/Article/ArticleID/41095/41095.html**

26

# Page Files

- What gets sent to the paging file?
  - Not code – only modified data (code can be re-read from image file anytime)
- When do pages get paged out?
  - Only when necessary
  - Page file space is only reserved at the time pages are written out
  - Once a page is written to the paging file, the space is occupied until the memory is deleted (e.g. at process exit), even if the page is read back from disk
- Windows XP (& Embedded NT4) can run with no paging file
  - NT4/Win2K: zero pagefile size actually creates a 20MB temporary page file (\temppf.sys)
  - WinPE never has a pagefile
- Page file maximums:
  - 16 page files per system
  - 32-bit x86: 4095MB
  - 32-bit PAE mode, 64-bit systems: 16 TB

27

# Why Page File Usage on Systems with Ample Free Memory?

- Because memory manager doesn't let process working sets grow arbitrarily
  - Processes are not allowed to expand to fill available memory (previously described)
    - Bias is to keep free pages for new or expanding processes
  - This will cause page file usage early in the system life even with ample memory free
- We talked about the standby list, but there is another list of modified pages recently removed from working sets
  - Modified private pages are held in memory in case the process asks for it back
  - When the list of modified pages reaches a certain threshold, the memory manager writes them to the paging file (or mapped file)
  - Pages are moved to the standby list, since they are still "valid" and could be requested again

28

# Sizing the Page File

- Given understanding of page file usage, how big should the total paging file space be?
  - (Windows supports multiple paging files)
- Size should depend on total private virtual memory used by applications and drivers
  - Therefore, not related to RAM size (except for taking a full memory dump)
- Worst case: system has to page all private data out to make room for code pages
  - To handle, minimum size should be the maximum of VM usage ("Commit Charge Peak")
    - Hard disk space is cheap, so why not double this
  - Normally, make maximum size same as minimum
  - But, max size could be much larger if there will be infrequent demands for large amounts of page file space
    - Performance problem: page file extension will likely be very fragmented
    - Extension is deleted on reboot, thus returning to a contiguous page file

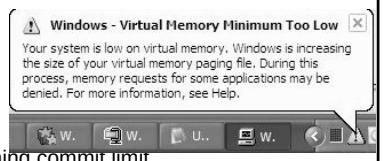
29

# Contiguous Page Files

- A few fragments won't hurt, but hundreds of fragments will
- Will be contiguous when created if contiguous space available at that time
- Can defrag with Pagedefrag tool (freeware - www.sysinternals.com)
  - Or buy a paid defrag product…

30

# When Page Files are Full

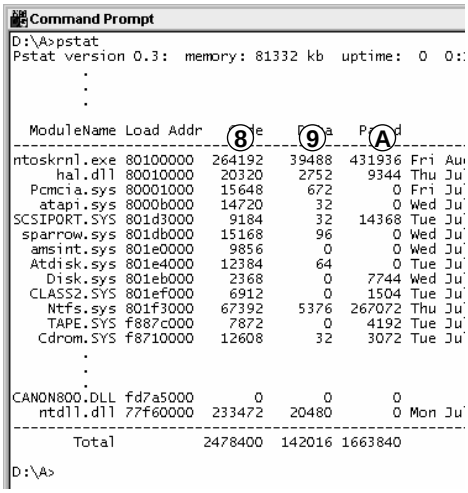



- When page file space runs low
  - 1. "System running low on virtual memory"
    - First time: Before pagefile expansion
    - Second time: When committed bytes reaching commit limit
  - 2. "System out of virtual memory"
    - Page files are full
- Look for who is consuming pagefile space:
  - Process memory leak: Check Task Manager, Processes tab, VM Size column
    - or Perfmon "private bytes", same counter
  - Paged pool leak: Check paged pool size
    - Run poolmon to see what object(s) are filling pool
    - Could be a result of processes not closing handles - check process "handle count" in Task Manager

31

# System Nonpaged Memory

- Nonpageable components:
  - Nonpageable parts of NtosKrnl.Exe, drivers
  - Nonpaged pool (see PerfMon, Memory object: Pool nonpaged bytes)
  - non-paged code
  - non-paged data
  - (8) pageable code+data (virtual size)
  - (9) output of "drivers.exe" is similar
  - (A) Win32K.Sys is paged, even though it shows up as nonpaged
  - Other drivers might do this too, so total nonpaged size is not really visible






# Optimizing Applications
## Minimizing Page Faults

- **Some page faults are unavoidable**
  - code is brought into physical memory (from .EXEs and .DLLs) via page faults
  - the file system cache reads data from cached files in response to page faults
- **First concern is to minimize number of "hard" page faults**
  - i.e. page faults to disk
  - see Performance Monitor, "Memory" object, "page faults" vs. "page reads" (this is system-wide, not per process)
  - for an individual app, see Page Fault Monitor:

```
c:\> pfmon /?
c:\> pfmon program-to-be-monitored
```

  - note that these results are highly dependent on system load (physical memory usage by other apps)

# Accounting for Physical Memory Usage

- Process working sets
  - Perfmon: Process / Working set
  - Note, shared resident pages are counted in the process working set of every process that's faulted them in
  - Hence, the total of all of these may be greater than physical memory
- Resident system code (NTOSKRNL + drivers, including win32k.sys & graphics drivers)
  - see total displayed by !drivers 1 command in kernel debugger
- Nonpageable pool
  - Perfmon: Memory / Pool nonpaged bytes
- Free, zero, and standby page lists
  - Perfmon: Memory / Available bytes
- Pageable, but currently-resident, system-space memory
  - Perfmon: Memory / Pool paged resident bytes
  - Perfmon: Memory / System cache resident bytes

  Memory | Cache bytes counter is really total of these four "resident" (physical) counters
- Modified, Bad page lists
  - can only see size of these with !memusage command in Kernel Debugger

34

# Further Reading

- Mark E. Russinovich and David A. Solomon, Microsoft Windows Internals, 4th Edition, Microsoft Press, 2004.
- Chapter 7 - Memory Management
  - Page Fault Handling (from pp. 439)
  - Working Sets (from pp. 457)
  - Memory Pools (from pp. 399)
  - Page Frame Number Database (from pp. 469)

35

# Source Code References

- Windows Research Kernel sources
  - \base\ntos\mm – Memory manager
    - Wslist.c, Wsmanage.c – working set management
    - Pfnlist.c – physical memory list management
    - Modwrite.c – modified page writer
  - \base\ntos\inc\mm.h – additional structure definitions
  - \base\ntos\cache – Cache manager

36